"Wear Plate" and Materials Selection for Sliding Abrasion

by Jeff Gates*

The Need for Wear-Resistant Materials

Given the highly abrasive nature of rock (both ore and overburden) handled in many mines, it is not surprising that abrasive wear accounts for a substantial proportion of maintenance costs in the mining industry. The direct costs of replacement consumables and labour for change-outs are often outweighed by indirect costs such as inventory costs and production losses due to machine unavailability. Even modest increases in service life have the potential to translate into significant improvements in mine profitability. In some cases, however, correct materials selection offers prospects for really major service life increases.

Wear plate is mostly used in applications

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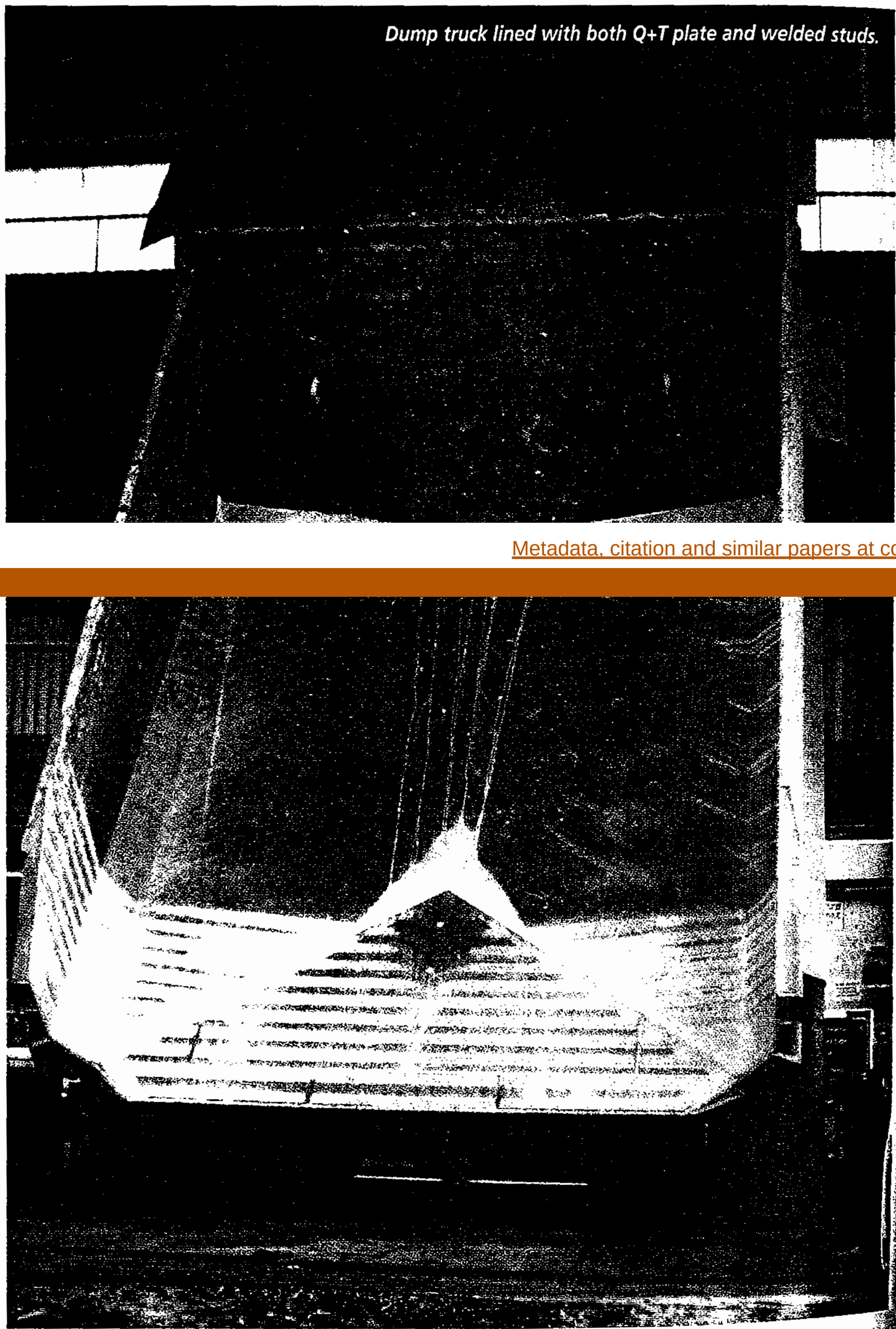

Dump truck lined with both Q+T plate and welded studs.

Types of Wear Consumables

Wear-resistant consumables can be made from metals (e.g. pearlitic steel, martensitic steel, NiHard cast iron), ceramics (e.g. alumina, basalt), polymers (e.g. natural rubber, polyurethane, HDPE) and composite materials (e.g. tungsten carbide – cobalt, alumina-filled resin). Metallic components can be broadly classified by their manufacturing method and shape into four groups:

(i) Castings — blocky or complex shapes, for components such as ground-engaging tools, liners for heavy crushing & grinding equipment, chrome-iron grinding balls, liner blocks for transfer chutes etc;

(ii) Forgings — steel grinding balls, miscellaneous components;

(iii) Rolled plate — liners & structural elements for buckets, skips, transfer chutes, bins, truck trays etc;

(iv) Hardfacing and fusion-clad plate — with uses as per (iii), plus application of wear-resistant surfaces in critical areas of larger components, plus rebuilding of worn components.

Wear Plate

"Wear plate" or "A.R. (abrasion-resistant) plate" typically describes flat products in thicknesses between 10 and 50 mm. Most commonly the term is used to describe rolled plate as per group (iii) above, but flat products can also be sourced from group (iv).

The advantages of wear plate (especially rolled, quenched-and-tempered martensitic steel plate) lie in the following:

- ability to cover large surface areas at relatively low cost;
- ease of cutting and forming to shape, installation and replacement by conventional fabrication technologies including bending, drilling, bolting and welding;
- a combination of hardness, yield strength and fracture toughness to permit use as light-weight structural elements with integral wear-resistant function;
- uniform and consistent properties.

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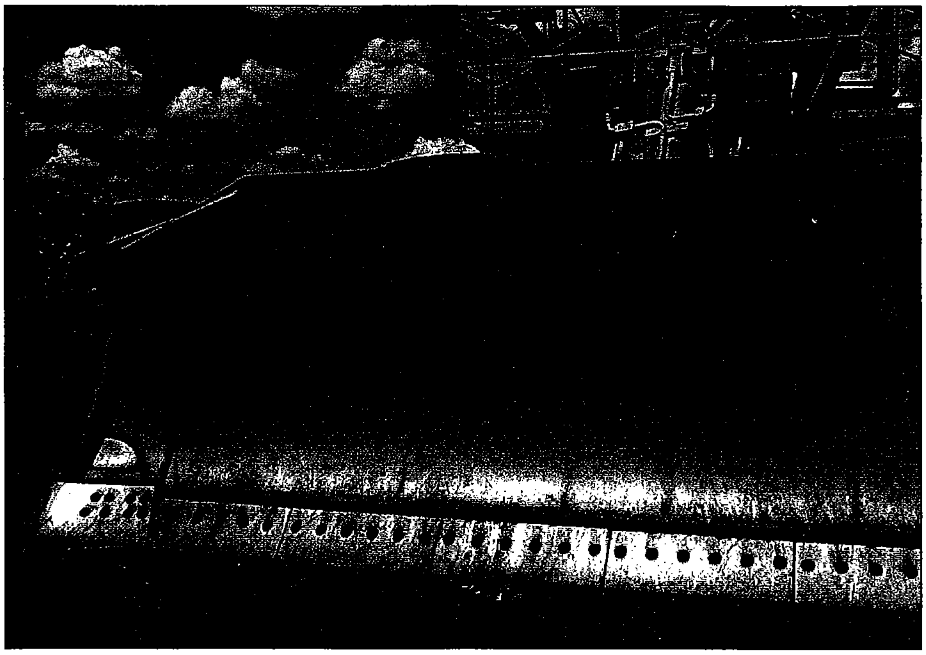
Martensitic Steel ("Q+T") Wear Plate

Rolled wear plate is usually made from low-to-medium-carbon low-alloy quenched-and-tempered (Q+T) steels. After an initial austenitising heat treatment (e.g. 900°C) they are rapidly quenched with water, resulting in the formation of an internal structure known as "martensite", which is very hard and abrasion-resistant. To obtain a fully martensitic structure within achievable quenching rates it is necessary for the steel to contain carbon and other alloying elements such as manganese, chromium, nickel and molybdenum. However, dedicated wear plate production facilities are able to obtain very high quench rates through the use of specially designed water sprays, so that low-cost lean-alloy steels can be used rather than more expensive alloys.



Dozer blade made from Q+T plate (image courtesy Total Steel Australia).

One of the important quality issues in martensitic steel wear plate is the through-thickness hardness profile.

Immediately after quenching, martensite may be hard but brittle, giving rise to the danger of component fracture — either spontaneously due to thermal distortion stresses, or under the influence of loads applied during installation and service. The ductility and toughness of the material can be recovered, with some sacrifice in hardness, by use of a "tempering" heat treatment (e.g. at 500°C). As with all wear-resistant products, hardness and wear-resistance must be balanced against fabricability and resistance to brittle fracture. These properties are controlled by adjusting the carbon content and tempering temperature — with higher carbon and lower tempering temperatures giving higher hardness but poorer ductility.

Abrasive Wear Mode

The optimal balance between hardness and competing properties such as ductility depends strongly on the type of abrasive wear occurring in the intended service environment. The following modes of abrasive wear can be identified:

A. Low-Stress Sliding Abrasion, such as occurs in chutes, excavation and general handling of loose granular minerals;
B. High-Stress Abrasion, occurring in crushing & grinding as well as in excavation of hard rock;
B2. Gouging Abrasion[1], occurring in primary crushers and in impact by very large rocks;
C. Solid Particle Erosion[2], occurring in slurry pumps, slurry pipelines, hydrocyclones, etc.
D. Impact-Abrasion[3], occurring in high-speed hammer mills and impact crushers.

Wear plate is mostly used for the first of these wear modes. In this wear mode, correct materials selection is very important, offering the opportunity for dramatic improvements in component life. For reasons that will be described below, the scope for service life increases through use of improved wear-resistant materials is much greater in low-stress sliding abrasion than it is in high-stress abrasion.

One might imagine that in low-stress abrasion the wear rates would be relatively low, and per tonne of ore handled it may be true that wear rates are higher in high-stress abrasion than in low-stress abrasion. However, in practice the linings of some chutes can suffer extreme wear rates, because of the high sliding velocities and the very high tonnages of ore passing across the metal every hour. In one mine, the NiHard cast iron wear blocks in a newly installed chute lost some 50 mm of thickness in a few days!

The very high wear rate in this case was a function of the high velocity, the very high density (specific gravity) of the ore, and the particular chute design. To understand this, it is necessary to understand something about the mechanics of the abrasion process. At the most fundamental level, three things are required for abrasion to occur: an abrasive particle that is harder than the plate being worn, a contact force to press the abrasive into the plate surface, and a sliding velocity required to cut a groove in the plate surface. It is important to note that whereas the sliding motion is parallel to the plate surface, the contact force is perpendicular to the surface.

In high-stress abrasion, the contact force is provided by a "counterbody", such as an opposing jaw plate or a grinding ball, which crushes the abrasive particle into the metal liner plate. Typically this results in high contact stresses and deep penetration, but relatively low sliding velocities. In low-stress abrasion (and similarly in particle erosion), there is no counterbody. In low-stress abrasion the perpendicular force required to press the abrasive particles into the liner surface is provided by the momentum of the particles as they fall onto the surface from a height or as they change direction at a bend in the chute. It should be noted that it is insufficient to speak simply of the "velocity" of the particles — it is necessary to give separate consideration to the perpendicular and parallel components of velocity.

"Rock-Boxing"

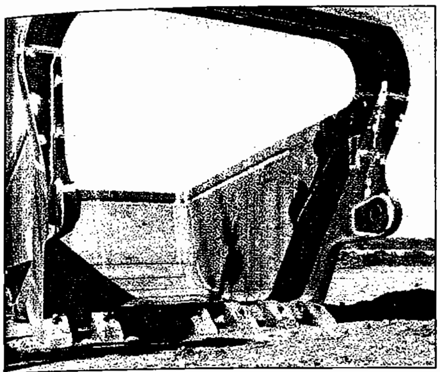
Another factor strongly influencing wear rate is the type of motion of the abrasive particles. If the particles move along the

[1] **Gouging abrasion** might be considered merely a subset of high-stress abrasion. It is characterised by contact stresses sufficient to cause extensive plastic deformation and/or brittle fracture of some materials, and by creation of very deep individual wear grooves.

[2] **Mode C** actually represents a wide range of conditions, depending on factors such as particle size, impingement angle and velocity. At low angles and velocities it can be very similar to mode A.

[3] **Wear mode D** is not well documented. It shares features with both modes B and C, but differs from B in terms of impact velocities (nominally greater than 10 m/s) and from C in terms of particle size (no clear cut-off value) and lack of fluid medium.

surface with a rolling motion, they will create a series of indentations in the surface but will not cut a continuous groove, so that the amount of metal actually removed from the surface will be relatively low. If on the other hand the particles slide



Dragline bucket lined with Q+T plate (image courtesy Bisalloy Steels).

across the surface in a fixed orientation, they can cut a continuous groove and wear rates will be much higher. Abrasive cutting tips will tend to maintain a fixed orientation when they are attached to large rock lumps that are sliding rather than rolling & bouncing across a surface, or when the abrasive particles are nipped between the liner and some counterbody as occurs in high-stress abrasion.

In chutes, one way of promoting a rolling, bouncing motion is to line the chute with horizontal bars ("rock ledges") with spaces between. The spaces trap rock and fines, creating a dead zone that can provide substantial protection against wear. Such a design feature is known as "rock-boxing". The overall ore velocity is reduced, and a potential disadvantage of this design is that in moist cohesive ores there is a tendency for hang-ups and bridging, causing the chute to block. In some cases where such blockages are common, productivity imperatives are deemed more important than maintenance costs and thus continuous-flow chutes may be favoure over rock-boxed designs. Rolled wear plate is best suited to continuous-flow designs, although segmented plates (tiles and blocks) of fusion-clad material might also be usable in rock-boxed designs.

The Importance of Hardness

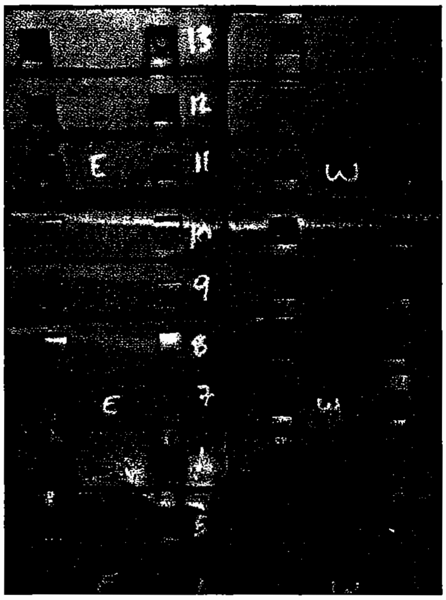
Abrasive particles cannot effectively penetrate the plate surface unless they are harder than the wear plate material. Thus hardness is a key property for a wear plate materials.

One of the important quality issues in martensitic steel wear plate is the through-thickness hardness profile. In thick-section products, quench rates are considerably lower in the core than in the near-surface material, and this can result in core hardness dropping below specified levels. The consequence of this can be accelerating wear rates through the product life, giving poorer total life than might be indicated by initial performance.

If a wear plate material can be found that is greater than 2/3 of the hardness of the abrasive mineral, wear rates can be reduced substantially. The difficulty of achieving this depends on the hardness of the mineral.

To quantify the level of plate hardness required, it can be noted that wear rates will be high whenever the abrasive hardness (measured in units of "HV", or Vickers hardness) is at least $1^1/_2$ times the hardness of the plate. Thus, if a wear plate material can be found that is more than 2/3 the hardness of the abrasive mineral, wear rates can be reduced substantially.

The difficulty of achieving this depends on the hardness of the mineral. Very hard quartzitic rocks can have hardnesses exceeding 900 HV, so a wear plate material with a hardness of greater than 600 HV would be required to control wear rates to acceptable levels. For many softer minerals, however, wear plate materials with hardness levels in the range 400 to 550 HV can provide good service. Indeed, once the ratio of plate hardness to abrasive hardness reaches about 0.8, little additional benefit is derived from the use of harder and more expensive products.



Chute lining with NiHard blocks, showing the effect of installation design.

Particle-Reinforced Materials

Most commercial martensitic wear plate products are limited to hardnesses of about 540 HV. This may not be sufficient to control wear by very hard abrasive minerals. Martensitic steels with hardnesses up to 700 HV or more are available, but they tend to be too brittle and/or difficult to fabricate for most wear-plate applications.

Products that contain very hard reinforcing particles in a more ductile matrix can very effectively prevent abrasion by most abrasive minerals.

As an alternative, materials are available that contain very hard reinforcing particles in a more ductile matrix. A particularly useful type of reinforcing particle is the chromium carbide Cr_7C_3, with hardness of the order of 1400 HV. Wear-resistant products including NiHard 4 & high-chromium white cast irons, and 2300-series hardfacing alloys, contain various amounts of chromium carbide particles. Although the bulk hardness of the mixture may be no greater than 600 HV, the presence of the hard reinforcing particles can very effectively prevent abrasion by most minerals. A wide variety of hardfacing alloys are available with various different reinforcing particles including chromium carbides, titanium carbides and tungsten carbides.

The degree of effectiveness of these particle-reinforced alloys depends on the operative wear mode. In high-stress abrasion, gouging abrasion and impact-abrasion it is often found that the high contact forces cause the reinforcing particles to crack, reducing their protective effect. Under such circumstances, only modest (e.g. 30%) improvements in life can usually be expected from the use of these materials compared to softer materials such as the pearlitic steels or austenitic manganese steels commonly used in such applications.

In low-stress abrasion, however, particle-reinforced materials can offer dramatic improvements in life compared to conventional martensitic steel wear plate. Life increases of up to 900% (i.e. 10 times the life) are achievable from a correctly chosen product.

Fusion-Clad Plate

These particle-reinforced materials generally require some kind of fusion (melt) processing to achieve the desired internal structure. This is offered both by castings and by hardfacing. Casting is very convenient for production of thick-section liner blocks, but the volume fraction of reinforcing particles is limited to about 35%; beyond this the fracture toughness is too poor and the castings will tend to break under installation or service forces. Higher volume fractions of hard reinforcing particles can be tolerated in hardfacing and clad products, where there is a ductile steel backing to provide structural support.

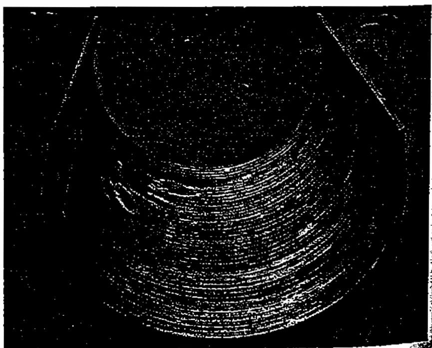
Hardfacing can be performed in-situ on critical parts of an existing component, but there is considerable convenience and cost advantage in pre-clad wear plate consisting of a layer of particle-reinforced material (typically 6 to 20 mm thick) on a mild steel backing (typically 6 to 12 mm thick). Such products are mostly used as longer-life substitutes for conventional martensitic steel wear plate. In smaller segments with integral studs protruding from the backing, they can be used to maximise wear life yet facilitate rapid change-outs in localised high-wear areas, while larger monolithic plate linings can be used for lower wear areas. A variety of attachment methods are available in off-the-shelf products.

Product Selection

In attempting to choose between conventional Q+T plate and particle-reinforced clad plate products, it should always be recognised that there is no single product that is best for all applications — it is "horses for courses".

Particle-reinforced clad plate products can offer superb performance in some environments, easily repaying their higher unit cost. As a guideline, it is in cases of low-stress sliding abrasion with harder abrasives that the performance of these particle-reinforced clad plate materials becomes outstanding. In some situations such as impact-abrasion, particle-reinforced clad products may perform quite poorly, giving higher wear rates than conventional Q+T plate. In intermediate cases, even though clad plate may perform somewhat better than softer steels, the small performance increase may not justify the increased cost. Especially in environments with softer abrasives, conventional Q+T plate may offer fully adequate service, providing little motivation to move to more exotic materials. Moreover, the advantages of formability and fabricability listed above for Q+T plate may not be obtainable from clad plate products, at least not to the same extent.

Some recently developed rolled wear plate products also make use of fine dispersions of very hard carbides. These may offer some advantages over conventional Q+T plate in resistance to fine abrasive particles. Other recently developed rolled plate products contain a proportion of retained austenite, which if present in sufficient volume fractions can provide wear performance advantages over what would be predicted from their initial bulk hardness. In all materials selection exercises it should be recognised that within a general class of product the specific products from different suppliers can have significant differences. Therefore, more than one option should be considered if best performance is to be obtained.



Roll-formed chromium-carbide-based dad plate (image courtesy AOA).

It is acknowledged that mining companies may find logistical advantages in restricting their inventory to a small number of standard wear-resistant products. Against this must be balanced the fact that such a policy will inevitably lead to sub-optimal performance in a significant number of cases. If the "standard" products being used across the board are being purchased to the same specifications as used for the last 20 years, then there is a very high likelihood that increased component life (and associated improvements in equipment availability) could be obtained through a review of product selection policies. After such review it might be possible to satisfy logistical constraints by standardising on limited number of products, but the new product list might look very different from that currently being specified.

Such a review would start with collection of information about the various products currently on the market, perhaps by contacting a range of suppliers and asking them to recommend products for the mine's particular ore and process conditions. The performance of the various candidate products should then be evaluated by some means, for example by laboratory testing. To be reliable, any abrasion tests must be conducted using the mine's own ore, not in idealised abrasives. Once a promising product (or short-list of candidates) is identified, field trials can be conducted prior to making final decisions. Obtaining meaningful performance data from field trials is a challenge, but can be successful if the trial is set up correctly.

Challenges for the Future

A wide variety of wear-resistant products are commercially available, and new improved products are continually being developed. An area of substantial recent and ongoing development has been in the area of fusion-clad products, utilising some of the newer weld-deposition and thermal spray technologies. Similarly, as mentioned above, there are some new developments in rolled plate products.

A challenge, both for the developers of such products and for their potential users, is to predict the likely performance of the new products compared to currently available materials. Given the difficulty and risk associated with field trials, predictive ability requires the availability of appropriate laboratory tests.

A challenge is to predict the likely performance of new products compared to currently available materials. It is doubtful whether any of the existing standard lab tests are able to provide reliable performance data for coarse particle-reinforced materials.

Standard laboratory abrasion tests suffer two significant limitations. Firstly, they only test one or two specimens at a time, which makes data generation slow & labour-intensive and can create problems with reproducibility and reliability. Secondly, most tests can only accommodate a very limited range of abrasive types and particle sizes. Laboratory tests performed in abrasives other than the actual ore being handled in service can produce results that are inaccurate and even misleading, giving rise to incorrect materials selection decisions.

Of the available standard tests for low-stress sliding abrasion, one of the best is the rubber wheel abrasion test (RWAT). This test can be a reasonable predictor of relative performance for materials such as pearlitic steels, martensitic steels and high-chromium white cast irons. However, it runs into problems when testing products such as hardfacing and ceramic-resin composites that contain very coarse granular reinforcement particles, such as coarse tungsten carbide. Initially only the softer matrix is worn by the test, so that the hard granular particles begin to stand proud. The protruding particles cut into the rubber wheel, damaging it. In such circumstances, the test will be unable to bring about the steady-state condition that would occur in service, whereby erosion of the matrix leads to fallout of exposed reinforcing particles resulting in accelerated matrix wear and so on.

It is in fact doubtful whether any currently available low-stress sliding abrasion test is able to provide reliable performance data for this important class of materials. The challenge for researchers is to design a test that can produce sufficient cumulative wear to reach the above-mentioned steady-state condition, while preserving true low-stress sliding abrasion conditions, and do so for several specimens simultaneously so as to generate reliable data.

Another challenge for the immediate future is to explore the possible use of some of these newer hardfacing deposits in high-stress abrasion situations. The benefits of particle-reinforced materials may not be as great in high-stress abrasion as in low-stress abrasion, but this is not to say they cannot be useful in such applications. Relevant performance data are lacking, because of a lack of suitable testing facilities. The most common laboratory tests purporting to simulate high-stress abrasion do not in fact produce performance data reflecting industrial high-stress abrasion conditions, and these tests seriously overestimate the benefits of particle-reinforcedmaterials. Recently, however, a test has been developed that does reproduce genuine high-stress abrasion conditions.Once this test is applied to hardfacing and fusion-clad materials, suppliers and users alike will benefit greatly from generation of relevant data.

Design of particle-reinforced materials to resist fine particle erosive wear presents different requirements from either high-stress abrasion or low-stress abrasion. This, however, is another story!

Conclusions

There is no single material or product type that is best for every application. Materials selection is a complex process requiring consideration of both the "science" of wear (wear modes, required hardness levels, optimal microstructures etc) and the "practical" issues (installation design, maintenance schedules, and of course cost). One of the keys to materials selection is availability of relevant laboratory test data. In the past this has been lacking, but recent developments show promise of new tests with better ability to predict service performance. AJM

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University tests put Bisalloy ahead of competitors

The University of Wollongong's metallurgy department recently conducted an extensive series of wear tests to benchmark the new improved Bisplate 360/ 400 and Bisplate 500 grades of wear plate against imported brands (both water and oil quenched) and alternative steel plate grades such as mild steel and weld overlay plates.

These experiments were conducted in accordance with the American Standards for Testing Materials (ASTM G65 - 86) - a low stress sliding abrasion wear test.

The University of Wollongong's metallurgy department definition of wear related to the hardness of the material, hardness of the particles wearing the surface and the pressure between the particle and the material surface. Material toughness was also found to be a significant factor in the wear resistance of steel plate.

In the 400 BHN range of plates, all the water quenched grades, such as Bisplate 360/400 performed similarly however the oil-quenched plate wore out 5-10% more quickly.

A more stark difference was observed in the 500 BHN range. Bisplate 500 performed the best, being up to 10% better than the Japanese and Swedish water quenched grades. The University's testers were most surprised at the poor level of performance of the European oil quenched 450/500 BHN grade, which performed 30% worse than Bisplate 500.

"These improvements can be attributed to continual incremental changes that Bisalloy has made to the chemistry and processing of its Bisplate range of plates over the last 2-3 years," said Nick Hardcastle, sales and marketing manager at Bisalloy Steels. "This has resulted in plates with better toughness, higher wear and better fabricability."

The improvements in Bisplate 500 were partly driven by extensive R&D work conducted on Bisalloy's range of armour plates to improve their ballistic performance. According to Bisalloy this was instrumental in its securing the supply of all the armour plate to the Australian Army's new generation of armoured vehicles, "Bushmaster".

The company also said that field trials in the most diverse range of applications - such as armour faced conveyor line pans, dump truck bodies, and iron ore and coal rail wagons - have been conducted, reinforcing these results. AJM

Hi-tech JFE products distributed by Total Steel

In late October 2002 the merger of two of Japan's leading steel-makers, Kawasaki and NKK, created a global steel giant called JFE Steel.

From a massive product range, of particular interest to the local mining industry is JFE Steel's range of leading-edge-technology wear and high strength plate distributed locally by Total Steel.

"Total Steel is dedicated to bringing the benefits of the latest in wear plate technology to Australasian industry," said John McMullan, deputy managing director, Total Steel. "Mining, construction and agricultural industries in this part of the globe demand high grade materials that perform efficiently and reliably in our unique, harsh conditions."

Total Steel stocks a wide range of JFE's wear plate products. The company also works closely with its customers advising on the best product for particular applications.

According to Mr McMullan, three particular JFE products give Total Steel an advantage in the Australian market.

EHSP Wear Plate, from 6mm to 65mm, contains titanium carbides that have a hardness of 3200 Vickers. These particles are dispersed throughout the steel plate during manufacture, giving EHSP, says Mr McMullan, a superior abrasion resistance when compared to plates with similar or higher Brinell (BHN) hardness.

"This plate can replace 320, 360, 400, 450 and 500 BHN in a large number of applications," commented Mr McMullan. "Introduced in 1995 EHSP has won end-user acceptance with many operations in the mining and quarry industries. The savings in labour and increased production through fewer change outs of wear plates has enabled maintenance personnel to channel their labour to other areas."

Introduced in March 2002, 360 LE and 780 LE from 6mm to 32mm are manufactured using micro-alloying technology and a controlled heat treatment process.

"These products represent some of JFE Steel's leading edge wear and high strength plate technology," said Mr McMullan.

"These grades give the end user greater economical advantages when compared to conventional style grades. Both the 360 LE and 780LE with CEQs of .4 to .43 allow excellent weldability, with no requirement for pre-heating.

"No longer will welding be an issue for